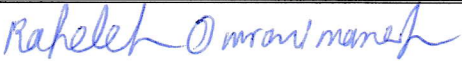




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MASTER'S THESIS

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Abstract

Robustness has become a requirement in the modern building codes. Despite significant theoretical and methodical progress in the recent years, structural robustness still has remained vague in its interpretation, evaluation and regulations. After the introduction of Eurocode in Sweden in 2011, the structural engineering community has had significant difficulties to apply the present rules, mainly because building practices are different from those in UK. The prescriptive tie requirements in Eurocode seem not to be technically suitable method in Sweden.

In this thesis, the feasibility of a risk-informed design approach for structural robustness has been examined for an actual case. The analysis has shown that in the ordinary buildings, the Eurocode requirements for structural robustness could simply be replaced by mitigation measures and independent check of a third party. Almost all construction failures in Sweden are attributed to gross errors in the building processes, therefore robustness is best controlled by quality control.

Engineering judgement plays a major role in the proposed approach. According to this method, design for robustness cannot be transferred into precise and generic rules as desired by structural engineers and authorities. It highly depends on specific properties of the building in a certain project.

Keywords: Structural robustness, disproportionate collapse, progressive collapse, risk assessment

Foreword

This master thesis was completed under the administration of the University of Stavanger and carried out at the Division of Structural Engineering at the Lund University. It was initiated in January 2016, under the supervision of Professor Terje Aven at the University of Stavanger and Professor Sven Thelandersson at the Lund University. The work presented in this thesis is related to an ongoing project at the Division of Structural Engineering of the Lund University with purpose to develop a design manual for structural robustness of buildings.

The completion of this thesis marks the end of my academic tenure as a master student at the University of Stavanger.

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1. Introduction

1.1. Background

Even small events can have catastrophic consequences. A structure should be capable to suffer local damage such as to prevent excessive spreading of it to other members. A disproportionate collapse refers to a situation where the consequences of the damage are disproportionate to the initial cause. A progressive collapse occurs when a local failure leads to an additional successive collapse of the entire structure or a major part of it. Progressive collapse can be initiated by many causes, including design and construction errors, gas explosions, vehicles collisions, sabotage, etc. The terms disproportionate collapse and progressive collapse are often used interchangeably.

The concept of progressive collapse has become concerned since the famous failure of Ronan Point building in London in 1968. A 22-storey building made of precast concrete bearing walls, suffered a gas explosion in a corner at the 18th floor. The upper floor slab fell on to the floor below and initiated the progressive collapse of one corner (Pearson and Delatte, 2005). In the wake of the Ronan Point accident, lack of provisions for general structural integrity was revealed. Although the Ronan Point failure was a progressive collapse, a more extensive class of failure, disproportionate collapse, became a major design criterion.

Although these types of failure especially during construction had occurred before, none of them made such an impression that the failure of Ronan Point building did on engineers and regulators (Canisius et al., 2007). In addition to potential for casualties in such a building, public perception issues were the main reasons for the sudden importance of progressive failures (MHLG, 1968).

More recently, the complete collapse of the World Trade Centre on 11th September, is a clear example of progressive collapse. As a result of the combination of impact damages, explosion of the aviation fuel and subsequent conflagration, the collapsing upper part of the towers caused a progression of failure extending down to the ground (Moore, 2002). Despite enormous consequences, arguably considered disproportionate

collapse because the initiating event was very extreme and could not reasonably be imagined to occur when the towers were built in the 1960s.

The complete collapse of twin towers highlighted the danger of having non-robust structures and led to a significant interest in the concept of robustness design of structures in the design codes and regulations. Robustness is a term which is often referred as the relationship between the initiating event and the overall consequences. Despite the substantial efforts on how to achieve structural robustness in recent years, unfortunately there is not an explicit guideline on how to achieve structural robustness yet and knowledge about robustness remains vague and scattered.

Structural engineers should be well aware of technical issues regarding managing low-probability, high consequences events and communicate the consequences to building developers, architects, and owners at the conceptual project design stage (Ellingwood, 2006). Clearly, in the presence of large uncertainties, there is a need for robustness, as it is difficult to predict the consequences and foresee exactly which scenario might happen in the future (Aven, 2014)

1.2. Definition of the problem

Robustness has become a requirement expressed in modern building codes. Accidental loading and design against progressive collapse is mainly treated in EN 1991-1-7 (CEN, 2006). Practical application for medium risk buildings (consequence classes 2a and 2b) is described in informative annexe A of the document, which is mainly developed on the basis of experiences from UK. After the introduction of Eurocode in Sweden in 2011, the structural engineering community has had significant difficulties to apply the present rules, mainly because building practices are different from those in UK.

The requirements on robustness in national standards should be country-specific. It is difficult to provide a general overview for all countries. The dominating system used in Sweden today for multistorey buildings includes precast concrete systems in which it is difficult to provide continuity and ductility. The prescriptive tie requirements in Eurocode seem not to be technically suitable method for these structures in Sweden. This overly simplified method may not provide the desired resistance even if they have significant economic consequences.

In Sweden, there is an increasing understanding of the need to investigate and improve current thinking and methods. Practising engineers frequently seek relevant guidance compatible to the Sweden's construction.

A good engineering practice involves looking beyond prescriptive code requirements and considering and analysing the potential risk of occurrence of accidental actions at the conceptual project design stage. A risk-informed approach toward structural robustness design leads to a design where the costs and risks are in balance.

1.3. Thesis objectives

At the division of Structural Engineering, Lund University, a project with purpose to develop a design manual for structural robustness of buildings is ongoing. They have been developing a guidance for the design of buildings with respect to accidental actions and progressive collapse in Sweden. They have pointed to weaknesses in current practices in Sweden and argued for the adoption of a risk perspective, providing alternative strategy toward structural robustness design. A key point in this perspective is the stronger weight given to the quality control compared to current thinking.

The aim of this work is verification of the methodology for an actual case and documentation of the experience from using the methodology.

1.4. Outline of the thesis

This report contains 6 chapters. Chapter 1 is an introduction to the topic. Chapter 2 provides some definitions of structural robustness and introduces general design approaches of structural robustness in modern day engineering as well as the Eurocode strategies in order to obtain structural robustness. Chapter 3 mainly focuses on the risk assessment framework and its different steps. It also describes different risk management strategies.

Chapter 4 describes the proposed risk-informed methodology for structural robustness for Sweden. Chapter 5 applies the proposed methodology for a real building in order to verify the methodology for a realistic case. Chapter 6 is a summary and discussion of results.

2. Structural robustness

There is a general consensus that structural robustness is not only of extreme importance but also the current situation concerning ensuring adequate structural robustness through codes and standards is highly unsatisfactorily (Faber and Narasimhan, 2011). Section 2.1 of this chapter reviews different definitions of structural robustness. Section 2.2 describes overall design approaches for structural robustness. Section 2.3 presents Eurocode design strategies to obtain robustness.

2.1. Introduction

Robustness is not only defined for Civil Engineering structures, but also for other fields and systems. Robustness, in general, refers to the insensitivity of performance to deviations from normal conditions and the word “robust” is often used for a system where the vulnerability is judged as low (Aven, 2008).

As mentioned earlier, there is no widely agreed definition of the structural robustness. As illustrated in Figure 2.1, robustness in structures can be considered to be related to several terms such as vulnerability, hazard, redundancy, accidental actions, etc. Robustness is clearly a vital factor in ensuring that the risks from failures in structures are acceptable. However, there are two generic viewpoints on this concept, the narrow view and the broad view. From the first perspective “structural robustness” is defined solely as the inherent property of structure, independent of accidental events and is a characteristic that does not deal with the structural performance of the individual elements, but how the elements interact and perform as a whole (Nafday, 2011, fib Bulletin 63, 2012). Second view extends the concept and robustness is defined as a measure of disproportionality between risks associated with an initiating event and any following up consequences to the structure. The latter considers the robustness from a life cycle properties and includes strategies for operation, maintenance and control as well as appropriate emergency response measures (Faber and Narasimhan, 2011). This broader view of robustness also includes considerations of extra-structural constituents (e.g. surrounding traffic network, environment, client, engineer, and municipality).

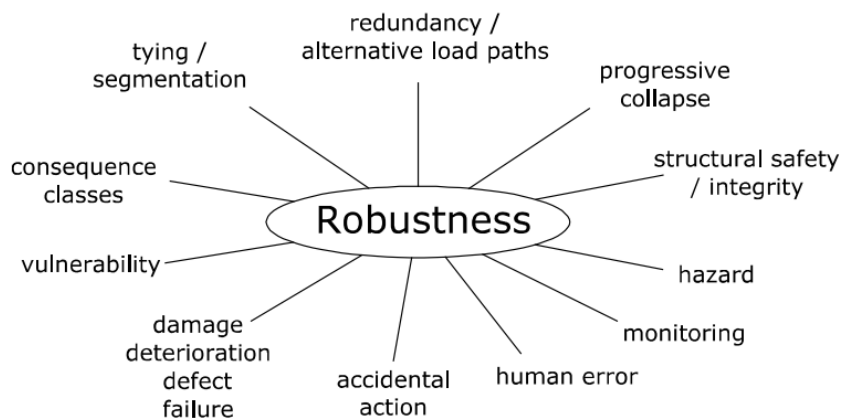


Figure 2.1. Illustration of robustness and related terms (Fink et. al., 2009)

There are several definitions of robustness concept in literature, some of them are presented here:

The European building standard Eurocode, EN 1991-1-7:

“Robustness is the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause”.

According to this code, “a localised failure due to accidental actions may be acceptable, provided it will not endanger the stability of the whole structure, and that the overall load-bearing capacity of the structure is maintained and allows necessary emergency measures to be taken.” (CEN, 2006)

International Organization for Standardization, ISO 22111 (2007):

“Ability of a structure (or part of it) to withstand events (like fire, explosion, impact) or consequences of human errors, without being damaged on an extent disproportionate to the original cause.”

Bontempi et. al, (2007)

“The robustness of a structure, intended as its ability not to suffer disproportionate damages as a result of limited initial failure, is an intrinsic requirement, inherent to the structural system organization.”

Starossek, (2009)

“Robustness is defined as insensitivity to local failure.”

Even though the information contained in these definitions may be substantial, it does not provide any criteria for an engineer to determine whether a system’s level of robustness is enough. What is common in the definitions is describing robustness based on the relationship between an event and subsequent consequences (Fink et. al, 2009)

2.1.1. Measures of robustness

Starossek and Haberland, (2011) presented the main measures of robustness which have been proposed in the past few years in order to examine a structure in terms of its robustness. Giuliani (2012) described the summary of definitions in four groups:

Risk-based: this approach relies on the definition “the consequences of structural failure should not be disproportional to the effect causing the failure” (Baker et. al, 2008). This method, therefore includes a measure of consequences in the calculation. It uses event tree for robustness quantification and divides the consequences into direct consequences which are associated with local component damage and indirect consequences which are associated with subsequent system failures. The assessment of probability for exposures as well as each scenario of the tree is required. Based on this approach “A robust system is considered to be one where indirect risks do not contribute significantly to the total system risk” (Baker et. al, 2008). The index of robustness (I_{Rob}) is defined as:

$$I_{Rob} = \frac{R_{Dir}}{R_{Dir} + R_{Ind}}$$

where R_{Dir} and R_{Ind} are the direct and indirect risks, respectively. These risks are defined as illustrated in Figure 2.2. First, an exposure occurs, if no damage occurs (\bar{D}) then there will be no consequences. If damage occurs (D) but the failure of the system does not occur (\bar{F}), there will be only direct consequences to the system. In the case of failure of the system because of damage, additional indirect consequences to the system are considered. Consequences typically come in several forms: inconvenience to system users, injuries, fatalities, and/or financial costs and can be combined into a scalar measure, termed utility/disutility.

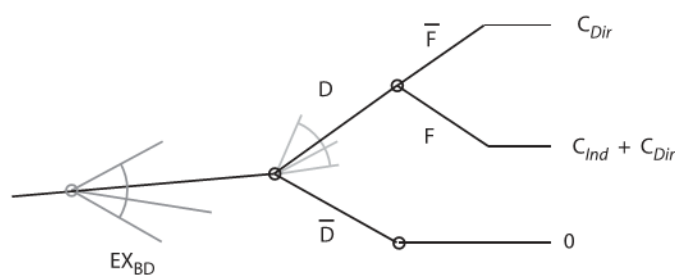


Figure 2.2. An event tree for robustness quantification (Baker et. al, 2008)

Topology-based: this method (Agarwal et al, 2003) is based on topological examination of the structure. In this method which is based on the theory of structural vulnerability, a hierarchical model of the structure is made based on the form and connections. Based on this model, the weaknesses and possible failure scenarios are recognized and described by vulnerability index. “Vulnerability is antagonistic to robustness and it is a property of structural system” (Starossek and Haberland, 2008)

Energy-based: several authors employed the concepts of energy absorption in the context of structural robustness. Smith (2003) proposed a methodology in order to assess the collapse resistance through energy principles. The main aim of this approach is to evaluate the critical sequence of damage events which lead to the structural collapse. More details about energy based approach can be found in Arup (2011), England and Agarwal (2008) and Izzuddin (2007)

Damage-based: this approach is based on the degradation of a parameter that represents the structural response, following a damage event. Several parameters for identifying both the response and the damage can be found in literature (Yan and Chang, 2006, Biondini and Frangopol, 2008).

2.2. Design for robustness

Robust design in general is an approach used by engineers to design systems and products. The foundation of the method is credited to Genichi Taguchi. Robust design aims to eliminate the sensitivity a product has to uncontrollable factors such as manufacturing variability and environmental conditions (Taguchi and Clausing, 1990). Design for structural robustness must not be considered as an over dimensioning of members but as the increasing the system's global safety against accidental events (Ioniță et. al, 2010). An important issue regarding incorporating robustness into current design method is lack of appropriate measures of quantification of robustness in structural systems which lead to subjective interpretations (Björnsson, 2010).

As pointed earlier, following the recommendations of the official inquiry into the Ronan Point failure, a number of countries implemented provisions on structural robustness and disproportionate collapse. Because of the elusive characteristic of the concept of system integrity, the codes and standards mostly deal with this issue in qualitative terms. Besides,

because of large diversity in structural systems the quantification of integrity has demonstrated to be difficult (Nafday, 2011).

Modern design codes are based on using structural reliability theory in order to estimate probability of failure. It is done by modeling statistical distributions to represent an action effect and the corresponding resistance (Starossek, 2006). One of the main issues with designing to resist disproportionate collapse is that the loading events in question are outside the scope of normal design. Starossek (2006) highlighted three reasons regarding inadequacy of current design codes for progressive collapse: 1- Modern design codes focus on member failure and they do not consider global failures. There is little guidance on the methods to consider system response and limiting consequences of the whole system, 2- because of the nature of probabilistic design, events with low probability and unforeseen events are not taken into account since statistical data is unavailable, 3- Finally, the current design methods depend on specified acceptable probabilities of failures. It is difficult to reach a true societal consensus and assign the admissible probability with regard to disproportionate collapse.

2.2.1. Quality control

As stated before, human error is the main reason of structural failures. Study shows that nearly 90% of structural failures have been caused by or human error or poor quality (Allen 1992). Failures due to mistake cannot be avoided completely as they seem to be inherent in the process of technological development, however adequate control and supervision of the design and construction processes minimises the possibility of errors (Beeby, 1999). According to Feld and Carper (1997) “As with all other construction materials, the best designs in precast and prestressed concrete can be ineffective unless the work done in the field is of high quality. If the design is marginal, construction deficiencies can compound the errors increasing the potential for serious problems...”

The effect of quality control must not be ignored and supplementary provision need to be implemented in order to minimize or even to eliminate the effect of design errors, execution errors, and unexpected deteriorations. As illustrated in Figure 2.3 quality control requirements should be covered in the codes in parallel with other requirements (Dean et al., 2011).

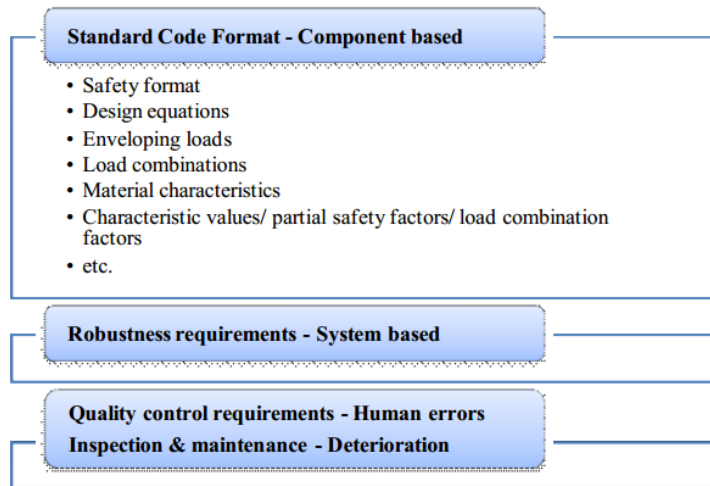


Figure 2.3. Code based design steps (Dean et al., 2011)

2.3. Design approaches

Design methods to prevent progressive collapse generally fall into four general categories based on recent literatures.

- 1- Prescriptive methods
- 2- Specific local resistance for the abnormal load in critical members
- 3- Develop alternate load paths (ALP)
- 4- Reducing the consequences

The first approach which is also referred as tie force approach, consists in applying design rules to increase the overall robustness of a structure, without performing an analytical computation for a specific load case. It is described more in detail in the next section. The second approach provides extra strength in the structures at areas that are believed to be prone to accidental loads or in key members that are necessary for overall stability and may be required to remain intact for alternate load paths to develop (fib Bulletin 63, 2012). The third approach focuses the attention of the designer on the behaviour of the structural system following the occurrence of the abnormal event (Ellingwood, 2006). The alternate load path approach consists in designing the structure so that stresses can be redistributed after the loss of a vertical bearing element. This method is independent of the hazard's type and since no actual loading is considered, the resistance provided by this method is not well assessed (McConnell and Brown, 2011). The last approach aims at reducing the consequences of collapse, e.g. through segmentation, emergency responses, etc.

2.3.1. Tying

Ties are continuous tensile elements consisting of reinforcing bars or tenders and ensure continuity of the structure during an event by allowing loads to be redistributed through alternative load carrying systems including catenary and vierendeel action. The capacity of the ties is a function of the self-weight, the imposed load, and the geometrical properties. It is the easiest method to implement as it does not require additional analysis of the structure (Byfield et. al, 2014).

Eurocode requires the building to be effectively tied around the perimeter of each floor and roof level and internally in two right-angle directions to tie the column and wall elements securely to the structure of the building. This requirement is not always beneficial and in some cases it may be preferable to compartmentalize the damage. For example, a part of the Murrah Federal Building in Oklahoma City collapsed because of a large bomb explosion. However, if the building had been further tied together, the whole building might have collapsed. Compartmentalization of failure is a design strategy that increases the robustness of some structural systems (Baker et. al, 2008)

2.3.2. Specific local resistance method (Key elements)

The third approach requires that key components whose notional removal would cause unacceptable collapse are designed to resist a prescribed hazard loading which may be in the form of explosions, impact, etc. The general design approach is to consider uniform pressure acting over their surface plus the surface of any attached items such as cladding. Hence, the structure is provided with additional strength in areas that are believed to be prone to accidental loads. Choosing a suitable type and magnitude of the accidental action is very important because the unforeseen nature of the accidental event may lead to designing key elements with inadequate resistance (Byfield et. al, 2014). The UK building regulations require that key elements are designed for a value of 34 kN/m² based on Ronan Point investigation results.

2.3.3. Alternative load path (ALP)

This method assumes that a local damage occurs in the structure due to accidental actions and an element such as a column is removed. The structure is required to redistribute all relevant loads in design with regard to progressive collapse (fib Bulletin 63, 2012). Each

supporting member should be notionally removed one at a time to ensure that the limit of admissible local damage is not exceeded and that the building remains stable. The dynamic resistance of the alternative load bearing system depends on the ductility of connections. One drawback of this method that is only one element at a time should be removed. One example that highlights this limitation is collapse of world trade centre towers where at least 36 columns and 31 to 36 columns were destroyed at the same time (Byfield et. al, 2014).

2.4. Eurocode design for robustness

The topic of robustness is essentially covered by two Eurocodes, EN 1990: Eurocode-basis of structural design (CEN, 2002) and EN 1991-1-7 Eurocode 1: Part 1-7 Accidental Actions (CEN, 2006). The former provides principles for achieving robustness and the latter provides provisions (strategies and rules) in order to obtain robustness. EN 1991-1-7 outlines the design criteria for achieving robustness, according to its assigned consequence class. The recommended procedures are based on the design approaches discussed in the previous section.

EN 1990, has the following requirements for structural robustness, without using the expression explicitly:

“(4) P A structure shall be designed and executed in such a way that it will not be damaged by events such as:

- explosions
- impact, and
- the consequences of human errors,

to an extent disproportionate to the original cause.

(5) P Potential damage shall be avoided or limited by appropriate choice of one or more of the following:

- avoiding, eliminating or reducing the hazards to which the structure can be subjected;
- selecting a structural form which has low sensitivity to the hazards considered;
- selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localized damage;

- avoiding as far as possible structural systems that can collapse without warning;
- tying the structural members together.”

EN 1991-1-7 describes the principles and application rules for the assessment of accidental actions on buildings and bridges. Besides, design load combinations for accidental loads are specified in combination with dead load and other loads. The code makes a clear distinction between identified and unidentified actions. The strategies to be considered for accidental design situations are illustrated in Figure 2.4. There are two design situations to be considered:

- strategies based on identified accidental actions,
- strategies based on unidentified actions (limiting the extent of localised failure).

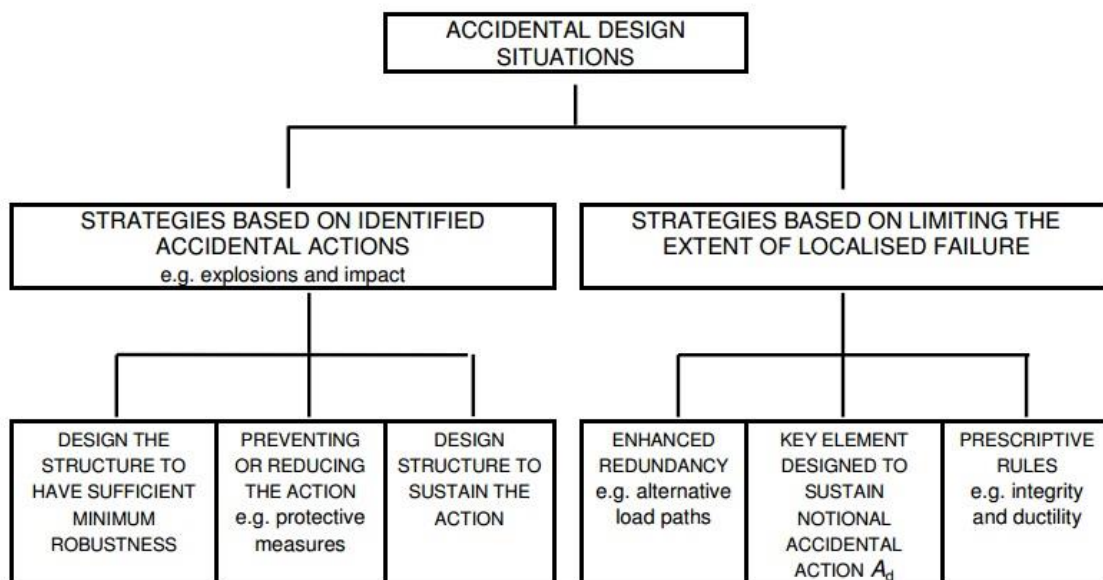


Figure 2.4. Strategies for accidental design situations in Eurocode (CEN 2006)

Strategies based on unidentified accidental actions aim to increase robustness without special consideration to loads or events that could initiate disproportionate collapse. These measures depend on the consequence classes which will be described in the section 2.4.1. This approach consists of applying prescriptive design rules to increase the structural robustness through increasing redundancy, design of special key elements and tying. However progressive collapse behaviour is not addressed explicitly.

2.4.1. Consequence classes

The EN 1991-1-7 provides a classification of buildings into four classes, based on the perceived consequences of failure. Design for robustness needs to be primarily included for structures with large consequences in terms of injury to human, damage to the environment and economic losses for the society. The building categorisation considers the building type, occupancy and size:

CC1 – single occupancy houses not exceeding 4 storeys, agricultural buildings, buildings rarely occupied by people etc.;

CC2a (lower risk group) – 5 storey single occupancy houses, hotels, flats, apartments, other residential buildings, offices not exceeding 4 storeys etc.;

CC2b (upper risk group) – hotels, flats, apartments and other residential buildings greater than 4 storeys but less than 15 storeys etc.;

CC3 – all buildings defined for classes CC2a and CC2b that exceed the limits on area or number of storeys, all buildings occupied by people in significant numbers, stadia for more than 5000 spectators, buildings containing dangerous substances and processes etc.

2.4.2. Strategies based on identified accidental actions

Chapters 4 and 5 of Eurocode EN 1991-1-7(CEN, 2006) provide standard design methods for impact (from vehicles, ships, trains, forklift trucks, and helicopters) and explosions. Rules were developed from the UK codes.

Annex C of the EN 1991-1-7 (CEN, 2006) gives guidance for the approximate dynamic design of structures to accidental impact by road vehicles, rail vehicles and ships based on simplified or empirical models.

Annex D of the EN 1991-1-7 provides guidance on how to deal with

- dust explosions in rooms, vessels and bunkers,
- natural gas explosions,
- explosions in road and rail tunnels.

According to chapter 5 and Annex D of the code, elements of a structure should be designed to withstand the effects of an internal natural gas explosions, using a nominal equivalent static pressure given by:

$$p_d = \max \left\{ \begin{array}{l} 3 + p_{stat} \\ 3 + 0.5p_{stat} + 0.04/(A_v/V)^2 \end{array} \right.$$

p_{stat} is the uniformly distributed static pressure in kN/m² at which venting components will fail

A_v is the area of venting component

V is the volume of room

2.4.3. Strategies based on limiting the extent of localised failure

The design for unidentified accidental actions is presented in Annex A of EN 1991-1-7 (CEN, 2006). Annex A, actually provides operational guidance only for consequence class 2. Based on the consequence classes, the following strategies are recommended (CEN 2006):

Class 1 buildings: No additional measures (Provided that a building has been designed and constructed in accordance with the rules given in EN 1990 to EN 1999 for satisfying stability in normal use)

Class 2A buildings: Provide effective horizontal ties for framed structures or effective anchorage of suspended floors and roofs to walls for loadbearing wall constructions

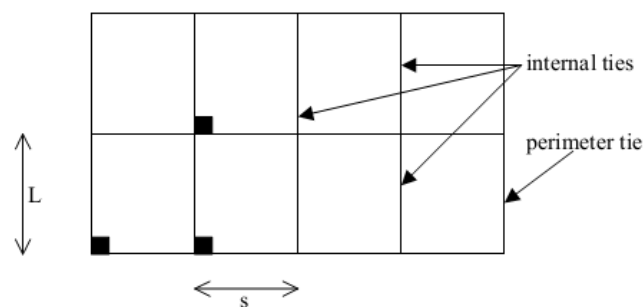


Figure 2.5. Example of horizontal tying of a framed building

Class 2B buildings: There are three methods by which the robustness requirements may be satisfied for Class 2B buildings.

- Provide effective horizontal ties, and effective vertical ties in all supporting columns.
- Check that upon the notional removal of a supporting column or a beam supporting one or more columns, or any nominal section of load-bearing wall (one at a time in each storey of the building), the building remains stable and that the area of floor at

any storey at risk of collapse does not exceed 15% of the floor area of that storey or 100 m², whichever is smaller, in each of two adjacent storeys.

- Where the notional removal of such columns (or beams supporting one or more columns) would result in damage in excess of the above limit, then such elements should be designed as key elements for a recommended accidental design action $A_d=34 \text{ kN/m}^2$.

The provision of horizontal ties in Eurocode implicitly relies on tensile catenary action and has no complementary requirements relating to joint ductility or joint rotation capacity. As this method is a simplified method, it is necessary to study further in order to verify the reliability of the method (Tohidi et. al, 2014).

According to Annex A EN 1991-1-7(CEN, 2006), Each continuous tie, including its end connections, should be capable of sustaining a design tensile load of “ T_i ” for the accidental limit state in the case of internal ties, and “ T_p ”, in the case of perimeter ties, equal to the following values:

Internal ties $T_i = 0.8(g_k + \psi_{qk}) s L$ or 75 kN, whichever is greater

Perimeter ties $T_p = 0.4(g_k + \psi_{qk}) s L$ or 75 kN, whichever is greater

where g_k and q_k are the characteristic values in [kN/m²] of the self weight and imposed load respectively; Ψ is the combination factor, s [m] is the spacing of ties and L [m] is the span in the direction of the tie, both in m.

Class 3 buildings: A systematic risk assessment of the building should be undertaken, taking into account all the normal hazards that can reasonably be foreseen, together with any abnormal hazards. Critical situations for design should be selected that reflect the conditions that can reasonably be foreseen as possible during the life of the building. There is currently no specific guidance on how to carry out the required risk assessment.

2-4-4. Systematic risk assessment

As mentioned in the previous section, the recommended procedure for class 3 structures requires the designer to perform a systematic risk assessment of the structure. However, there is not a clear guidance. As illustrated in Figure 2.6 a building is subjected to an exposure such as explosion, impact, etc. (a). The vulnerability of a structure (b) is described

through the degree the structural members are damaged by the effects of the exposures. The structural robustness is described as the capacity of the structure to sustain the damage without partial or full collapse. As mentioned before, the current design codes are implicitly addressing vulnerability aspects and are mainly focusing on component failures.

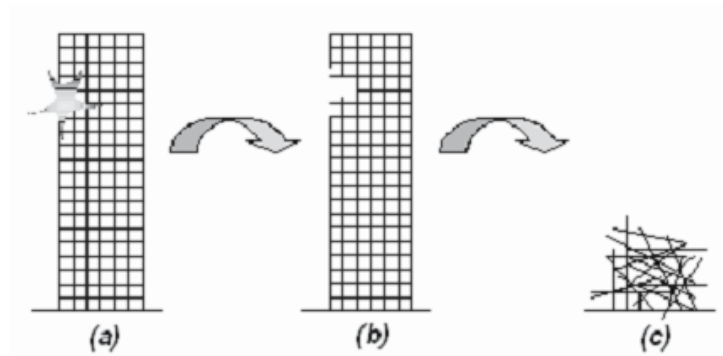


Figure 2.6. Illustration of exposure, vulnerability and robustness

A general overview of risk assessment provided by EN 1991-1-7 (CEN, 2006) is presented in Figure 2.7. The recommended steps for a systematic risk assessment are:

- Definition of scope and limitations
- Qualitative risk analysis
- Quantitative risk analysis
- Risk evaluation and risk treatment
- Risk communication

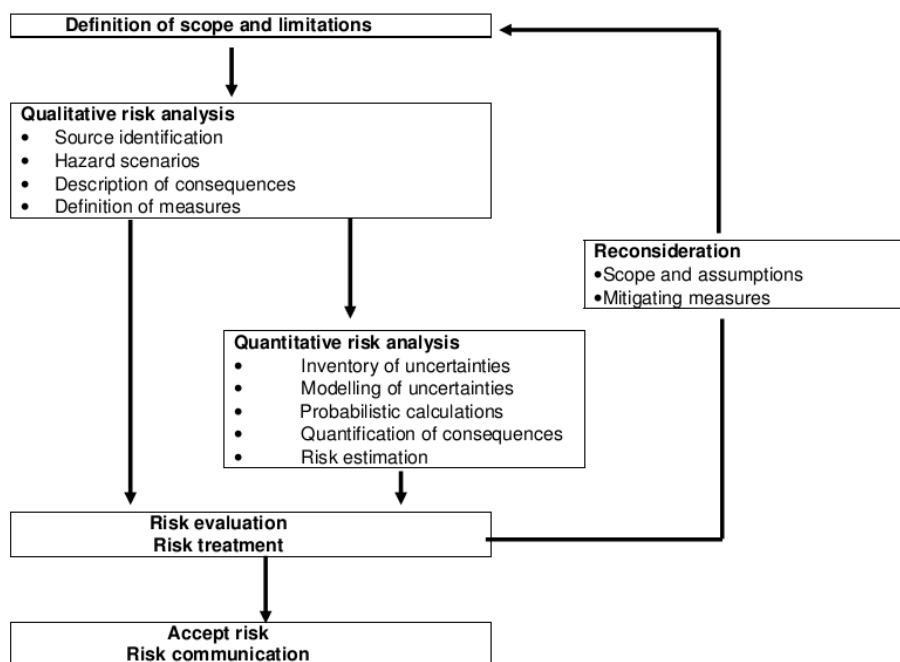


Figure 2.7. Overview of risk analysis (CEN, 2006)

According to EN1991-1-7 (CEN, 2006) Risk is defined as a measure of the combination of the probability or frequency of occurrence of a defined hazard and the magnitude of the consequences of the occurrence and is expressed as:

$$R = \sum_{i=1}^{N_H} p(H_i) \sum_j^{N_D} \sum_{k=1}^{N_S} p(D_j|H_i)p(S_k|D_j)C(S_k)$$

where:

N_H – number of different hazards

N_D – number of ways the hazards may damage the structure,

N_S – number of adverse states (S_k)

$C(S_k)$ – consequences of an adverse state

$p(H_i)$ – probability of occurrence (within a reference time interval) of the i^{th} hazard

$p(D_j|H_i)$ – the conditional probability of the j^{th} damage state of the structure given the i^{th} hazard

$p(S_k|D_j)$ – the conditional probability of the k^{th} adverse overall structural performance S given j^{th} damage state

Based on the above definition of risk, different strategies for risk control, and risk reduction need to be investigated for economic feasibility through risk assessment:

- risk may be reduced by reduction of the probability that the hazards occur i.e. by reducing $p(H)$
- risk may be reduced by reducing the probability of significant damages for given hazards, i.e. $p(D|H)$
- risk may be reduced by reducing the probability of adverse structural performance given structural damage, i.e. $p(S|D)$

3. Risk- informed approach on robustness

All designers attempt to make a balance between risks and consequences. They try to do so either explicitly through a risk assessment process or implicitly through interpretation of the regulations and codes and standards (Moore, 2002). Risk assessment provides important contributions in supporting decision-making in practice. This chapter first provides a few qualitative definitions of risk and then in section 3.2 a general overview of risk assessment framework is described. Section 3.3 discusses about black swan in the risk context. Section 3.4 discusses about different risk management strategies and especially in situations with high uncertainty. At the end, qualitative risk assessment as well as risk communication are briefly described.

3.1. Introduction

The term risk is used frequently in daily life and professional context. There exist several definitions of “risk” in the literature. Society for Risk Analysis (SRA, 2015) presents overall qualitative definitions of risk as follow. What is common in most of the definitions is uncertainty about events and consequences:

- (a) the possibility of an unfortunate occurrence,
- (b) the potential for realisation of unwanted, negative consequences of an event,
- (c) exposure to a proposition (e.g. the occurrence of a loss) of which one is uncertain,
- (d) the consequences of the activity and associated uncertainties,
- (e) uncertainty about and severity of the consequences of an activity with respect to something that humans value,
- (f) the occurrences of some specified consequences of the activity and associated uncertainties,
- (g) the deviation from a reference value and associated uncertainties.

Ellingwood (2006) highlighted the role of risk-informed decision making in order to assess and mitigate risk from low-probability, high-consequence events for buildings. He stated: “It is not feasible technically or economically to design a building for all hazards that might impact its performance. Indeed, the vast majority of buildings are not threatened by abnormal load events that are likely to lead to collapse, and thus only a fraction of buildings

would require additional structural engineering to achieve progressive collapse-resistance performance objectives”.

The main purpose of a risk assessment is to produce a risk description which is utilized by decision-makers and stakeholders in order to support the decision-making and their views on relevant issues such as choosing between alternatives, the acceptance of activities and products, the implementation of mitigation measures (Aven, 2016). The result of risk assessment informs the decision maker, but it is not considered as prescription of what to do. (Aven, 2014)

Figure 3.1 provides a better understanding of relation between risk assessment and risk management process (ISO 31010, 2009).

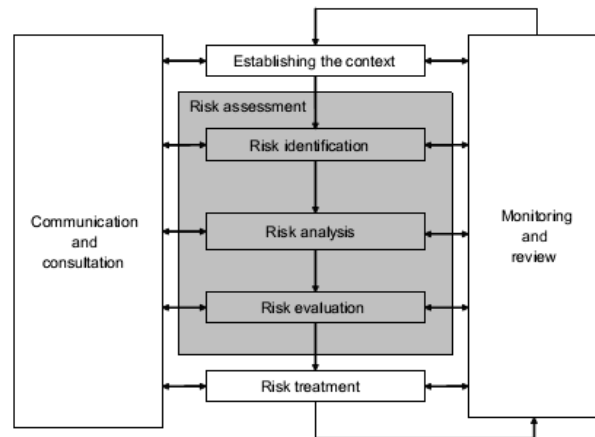


Figure 3.1. Contribution of risk assessment to the risk management process (ISO 31010)

The purpose of a systematic risk assessment of a building project is to identify and analysis the potential risk of occurrence of accidental actions and their associated effects. The results of the analysis may help to choose a design strategy in order to mitigate the risk of progressive collapse (fib Bulletin 63, 2012). The systematic risk assessment is a requirement of Eurocode EN-1991-1-7 just for buildings in consequences class 3(CEN, 2006).

3.2. Risk assessment framework

Figure 3.2 shows the main steps of the risk analysis process which more or less can be found in the text books (Aven, 2008). The main steps in the risk assessment are briefly described in the following:

System and context definition- When performing a risk analysis, it is important to include a description of the system of interest and the context in which it is situated. The system does not necessary means the technical system. Context, on the other hand, includes the external environment of the system which cannot be influenced easily by the decision maker (Tehler, 2015).

This step includes description of structural and functional systems of the building and all assumptions regarding the system representation and idealizations. From such a description the following aspects are of concern (fib Bulletin 63, 2012):

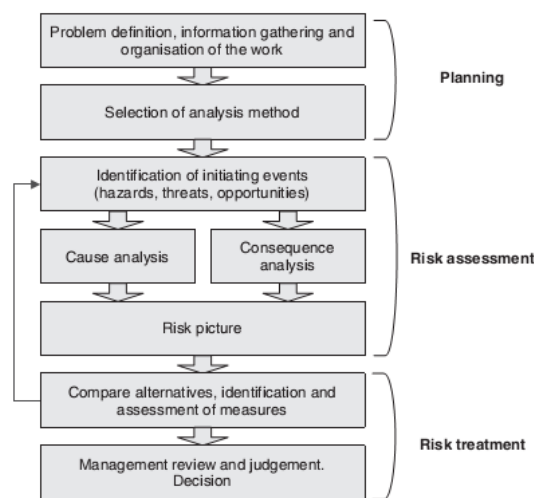


Figure 3.2. The main steps of the risk analysis process (Aven, 2008)

- The strategic role of the building following an accidental loading event, e.g. transport, healthcare, energy supply, etc.
- The possibility of large numbers of human casualties, e.g. shopping centres, stations, etc.
- Technical description of the structure, e.g. structural form, connections, heights and spans, material, etc.
- The possibility of terrorist actions, e.g. embassies, governmental buildings, etc.

Selection of analysis method- The risk assessment method should have sufficient details. The complexity of assessment should be proportionate to the complexity of the problem. The types of risk assessment are (fib Bulletin 63, 2012):

Qualitative: the search for the weak spots takes place without the quantitative weightings,

Semi-quantitative: the likelihood and consequences are approximated within quantified ranges,

Quantified risk assessment: the effects of an accident (collapse) are quantified and the chance of risk occurrence is estimated.

Identification of initiating events- The main step in the risk assessment process in relation to disproportionate collapse is to identify the hazards. Although following a standard approach to hazard identification would be helpful, this process should be a creative step and it is important to avoid this task become a routine. Failure to do so, one may ignore special aspects and features of the system being considered (Aven, 2008). There exist several methods for carrying out such an identification process such as FMEA, HAZOP and SWIFT. The list of possible hazards in buildings is described in the next chapter. It is well known that human error is a main initiating event for disproportionate collapse (Schneider, 2006)

Cause and consequence analysis- Several techniques exist in order to identify the causes and the possible effects of each event such as brain-storming sessions, event tree analysis and fault tree analysis. This is usually done using a bow-tie analysis. Figure 3.3 illustrates a simple bow-tie diagram with Fault Tree and Event Tree. This analysis could provide a basis for assessing the need for measures to reduce the probability of initiating events and also barriers in order to reduce the severity of the consequences (Aven, 2008). In other areas of the structural engineers' work even minor consequences are important and need to be taken into account. Typical consequences are economic consequences, loss of life and effects on the environment.

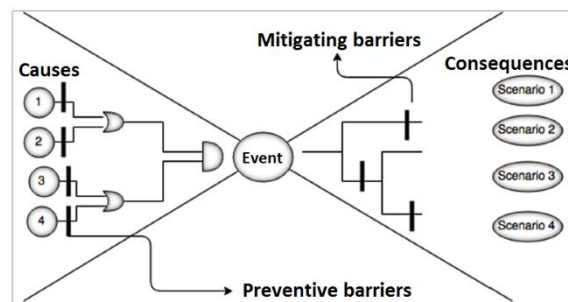


Figure 3.3. The bow-tie diagram with barriers

Risk picture- the purpose of risk presentation is to facilitate understanding and communication of risk level and also evaluation and decision-making. A possible way of presenting risk is Risk Matrix.

Risk evaluation- concerns comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable (ISO 31000, 2009)

Risk management- having identified risk, it is necessary to implement measures in order to eliminate or reduce the severity of the consequences. This step is described more in the next section.

3.3. Risk management

Risk management includes all measures and activities carried out in order to manage risk. Risk management is often a challenging process as often involves decision-making in situations characterised by high risk and large uncertainties where it is difficult to predict the consequences (Aven, 2008). Risk management is briefly defined as systematic measures undertaken in order to achieve an acceptable degree of risk. In general, there are three strategies toward managing risk (SRA, 2015):

- Risk-informed,
- Cautionary/precautionary
- Discursive strategies.

In most cases, the combination of these strategies is carried out. The risk-informed strategy uses risk assessments in order to handle risk through avoidance, reduction, transfer and retention (SRA, 2015). The result of risk assessment is used as an input for a broader managerial review and judgment as well as decision analysis tool such as cost-benefit analysis. As mentioned earlier, the result is informative and is not considered as a prescription of what to do (Aven, 2014). Cautionary/precautionary strategy is derived from “caution” principles and is also referred to as robustness and resilience strategy. Obviously the level of caution has to be in balance with other concerns such as costs (Aven, 2014). It focuses on redundancy, developing substitute, increasing knowledge, safety factors, etc. “The discursive strategy uses measures to build confidence and trustworthiness through reduction of uncertainties and ambiguities, clarifications of facts, involvement of affected people, deliberation and accountability” (SRA, 2015).

The ALARP principle (As Low As Reasonably Practicable) is a commonly adopted risk reduction principle, founded on both risk-informed and cautionary/precautionary thinking (SRA 2015).” The principle is based on the idea of gross disproportion and states that a risk-reducing measure shall be implemented unless it can be demonstrated that the costs are in gross disproportion to the benefits gained” (Aven, 2014).

In structural applications, the system, the system response, the cause–effect relationships, the hazards and the consequences are usually subject to considerable uncertainty (Ioniță et al, 2010). Aven categorises risk problems based on the degree of uncertainty and presents management strategies and appropriate instruments for each category. Large uncertainties refer to situations in which the knowledge base is poor, and reliable predictions cannot be made. The proposed management strategies for situations with large uncertainties are illustrated in Table 3.1 (Aven, 2014).

Table 3.1. The illustration of management strategies for a risk problem in the large uncertainty group (Aven, 2014)

Risk problem category	Management strategy	Appropriate instruments
Large uncertainties	Risk informed and Caution/Precaution based (risk agent)	Risk assessments. Broad risk characterisations, highlighting uncertainties and features like persistence, ubiquity etc. Tools include: <ul style="list-style-type: none"> • Containment • ALARP (as low as reasonably possible) • BACT (best available control technology), etc.
	Risk informed. Robustness and Resilience focused (risk absorbing system)	Risk assessments. Broad risk characterizations. Improving capability to cope with surprises <ul style="list-style-type: none"> • Diversity of means to accomplish desired benefits • Avoiding high vulnerabilities • Allowing for flexible responses • Preparedness for adaptation

3.4. Surprises and black swan

Black swan refers to the unexpected, catastrophic event that seems no one plans for it. Taleb who is well known for popularizing the Black Swan concept, defines the black swan as an event with the following three attributes (Taleb, 2007):

- “1. First, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility.
2. Second, it carries an extreme 'impact'.

3. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable.”

Aven (2013) refers to a black swan as a “surprisingly extreme event relative to one's belief/knowledge”. Aven and Krohn (2014) divided the surprises into three categories:

a) Unknown unknowns are type of events that are completely unknown to the scientific environment (unknown unknowns),

b) Unknown knowns- (unknown events to some, known to others) are type of events which are unknown in the view of those who carry out a risk analysis but known to others,

c) Events which are on the list of known events but judged to have a very low probability of occurrence, and thus not believe to occur so that they are ignored.

It is clear that managing these types of risks are not straightforward. In order to confront black swan events, the best approach is to balance between the risk management strategies risk-based approaches, cautionary/precautionary (robustness, resilience, adaptive) and discourse-based approaches which were described in section 3.3. In the case of unknown unknowns where both consequences and uncertainties are high, increasing scientific knowledge and focusing on robust and resilient solutions, signals and warnings provides useful general means. In the case of unknown known type, the quality of risk assessment and communications for transferring knowledge to relevant people are two potential areas for improvement (Aven, 2015a).

As Aven highlighted (Aven, 2015b), ”the basic idea of addressing black swans is to obtain a stronger focus on issues not covered by the traditional risk perspectives”. Ronan point accident is a good example of black swan events. What is informative is to remember that such a minor event can lead to building collapse despite being designed for all the extreme scenarios conjectured in building codes (Nafday, 2011).

3.5. Qualitative risk assessment

Qualitative risk analysis includes a simplified risk analysis and standard risk analysis method. A simplified risk analysis, which is an informal process, includes brainstorming sessions and group discussions. The standard risk analysis is a more formalised procedure which uses several risk analysis tools such as fault tree analysis, event tree analysis,

HAZOP, etc. A qualitative analysis in many cases provides a sufficient basis for identifying which measures to implement.

3.6. Risk communication

Risk communication refers to sharing the information about risk with decision makers and stakeholders. Aven (2014) describes the importance of a proper platform for risk communication, i.e. if a solid platform exists; it is much more likely that risk communication will work effectively as the premises for the dialogue are clear. Provided that the risk analyst does his/her job in a professional way, regardless if the decision-maker possesses fundamental training in risk or not, the risk communication can be informative.

4. Proposed methodology for Sweden

The proposed approach aims at introducing a systematic approach to identify hazards leading to progressive collapse in buildings and evaluate prevention and mitigation measures. The current approach relies on risk-based thinking. It requires a detailed consideration of each building rather than only following the rules. This means a qualified assessment should always be conducted in the early stage to identify hazards that may occur with respect to the building's activities, location and characterisation.

A main principle here is that the results from the risk assessment are well documented and communicated ensuring that it can be reviewed by an independent party who does not participate in the construction project.

4.1. Risk-informed approach

Similar to Eurocode 1991-1-7 (CEN, 2006), the proposed approach divides the extreme events into two categories: identifiable events and unidentifiable events. The main idea is that all accidental events are evaluated and if identified hazards can not be eliminated, the associated risks have to be managed in an explicit investigation.

4.1.1 Hazard identification

Table 4.1 provides a list of possible hazards and threats that buildings are exposed to. However, the list is not claimed to be complete. The hazards written in bold letters are addressed explicitly in the Eurocode.

Category 0 presents normal loads such as wind, snow, etc. These events are described on the basis of available statistical data. The hazards categorized in this category do not need to be considered in the risk assessment as it is assumed that the construction work is designed or will be designed to withstand normal loads.

Category 1 consists of extreme events related to natural causes or human activities. Examples of unintentional impacts from human activities are fire, collisions and explosions. Extreme natural events include hurricane, flood, landslide, etc.

Category 2 includes intentional actions caused by humans, such as terrorist attacks and vandalism. The occurrence of these events have been increased in the recent years.

Category 3 consists of various types of human errors related to the building processes and is directly related to the effectiveness of quality control and degree of supervision.

Table 4.1. Classification of undesirable events (Boverket, 2016)

0	1		2	3
Normal loads	Accidental events		Deliberate actions	Errors in the building processes
	a) Natural Causes	b) Human causes		
<ul style="list-style-type: none"> • Self weight • Imposed load • Traffic Load • Snow load • Wind load • Hydraulic loads • Earth pressure • Temperature Load • Shrinkage etc. 	<ul style="list-style-type: none"> • Earthquake * Landslide * Avalanche * Tornado, * Hurricane, * Cyclone * Flood * Erosion * Eruptions etc. 	<ul style="list-style-type: none"> • Collision of: <ul style="list-style-type: none"> - road vehicles - train - Ship - aircraft • Internal explosion (gas and dust) <ul style="list-style-type: none"> * External explosion * Geotechnical instability • Internal fire¹ <ul style="list-style-type: none"> * External fire etc. 	<ul style="list-style-type: none"> * terrorist attacks * Vandalism * Riot etc. 	<ul style="list-style-type: none"> * design error * Execution errors * Material error * misuse * Deficiencies in maintenance * Deficiencies in communication and organization etc.

4.1.2. Identifiable events

A systematic review of hazards should be undertaken for the events in the category 1 of Table 4.1. The assessment of identifiable accidental events is performed according to the flowchart in Figure 4.1. The assessment involves a simple risk screening procedure along with describing appropriate risk mitigation measures (Boverket, 2016).

4.1.3. Unidentifiable events

Unidentifiable events include category 2, "deliberate actions", and category 3, "errors in the building processes", of Table 4-1. Both categories are in principle known and predictable, but they cannot be described in such a way that their associated risks can be managed with conventional methods. Moreover, there are also unknown unknowns in this category which are unknown in nature and can not to be described explicitly. However, it is reasonable to exclude unknown unknowns from the list of hazards for ordinary buildings (consequence class 2a or 2b) (Boverket, 2016).

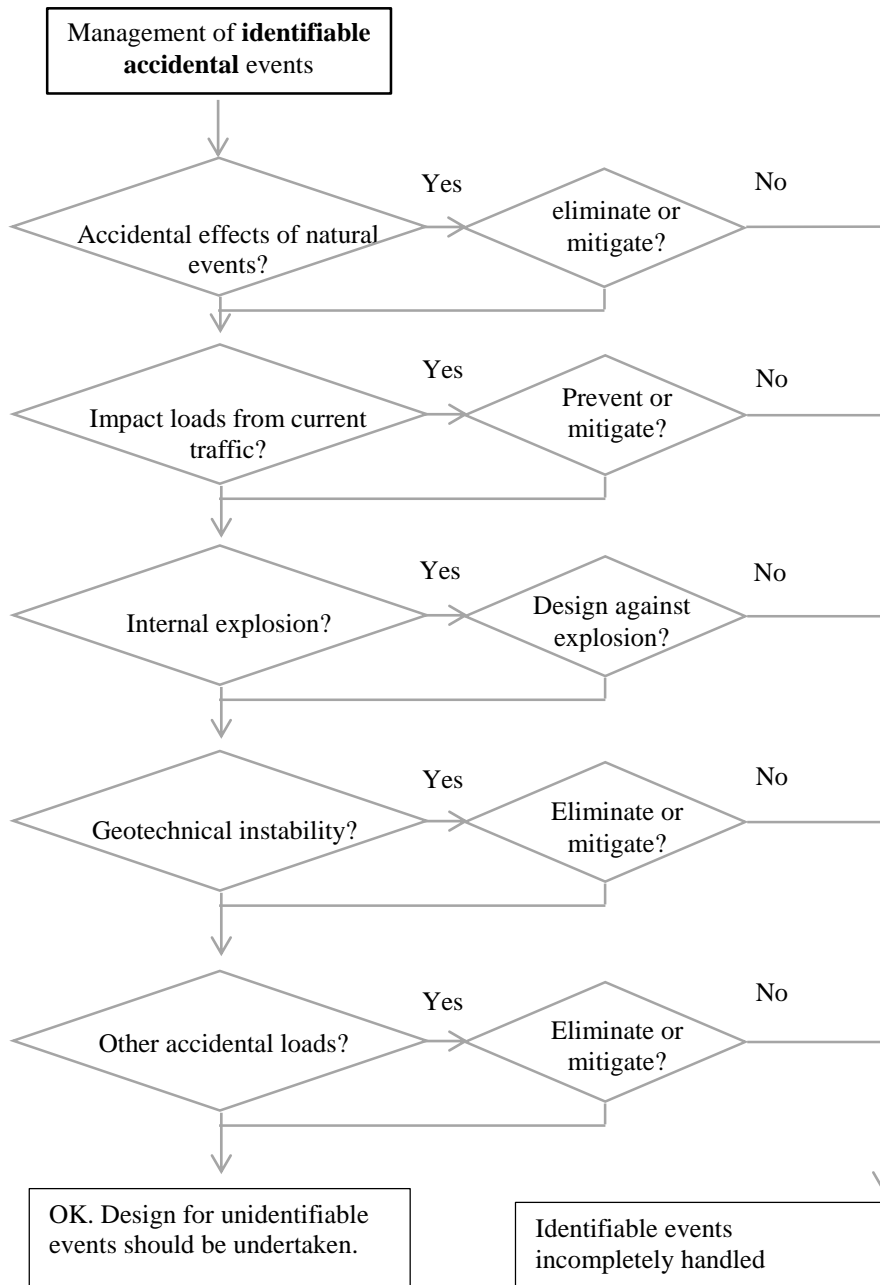


Figure 4.1. Management of identifiable accidental events (Boverket, 2016)

As stated before, the main strategy proposed in EN 1991-1-7 (CEN, 2006) against unidentifiable events is to limit the consequences of hypothetical local failures by designing the structural frames according to prescriptive rules, e.g. enhanced redundancy, etc. see section 2.4.3.

The proposed alternative strategy here is “*risk-informed approach*”. This strategy aims at reducing the probability of occurrence of “unknown knowns” through preventative control measures instead of focusing on the consequences. In many cases, the prescribed rules can

easily be replaced by risk mitigation measures, mainly by reducing the likelihood of errors in the building processes (Boverket, 2016)..

To summarize, design for structural robustness can be divided into two strategies (for consequence class 2a and 2b):

1. Risk-informed approach,
2. Direct application of the rules of Eurocode EN 1991-1-7(CEN, 2006).

Figure 4.2 illustrates the indicated management strategies for structural robustness.

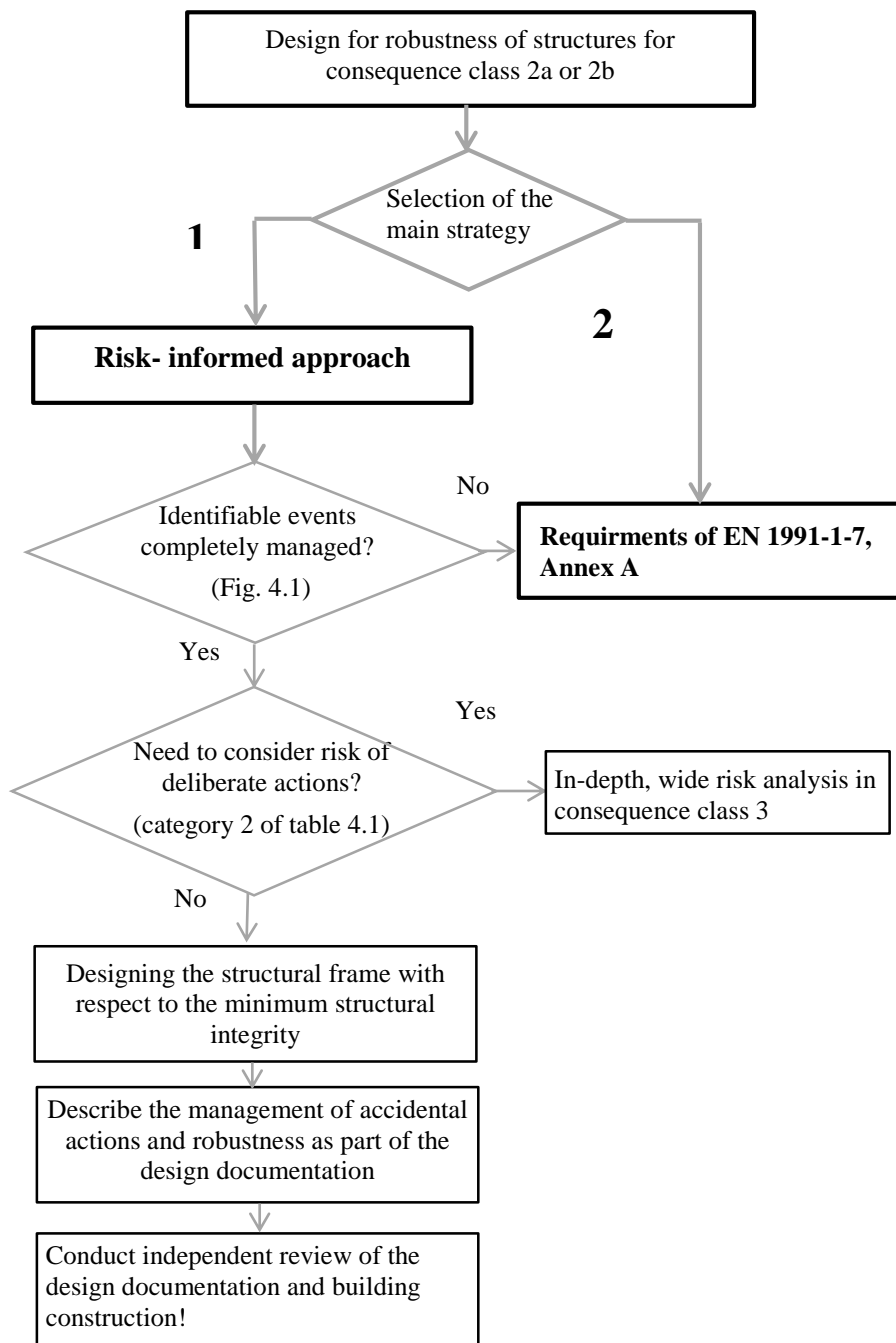


Figure 4.2. Management strategies for structural robustness (Boverket, 2016)

Risk-reduction through control measures approach

If one chooses to manage robustness through strategy 1, the important question is whether to consider the risk of deliberate actions or not. The building might be critical to the owner or a third party. Therefore, evaluation of probability of deliberate actions for a specific building should be made in consultation with the building owner. If one decides to consider this risk, the building should be treated as a building in consequence class 3, i.e. implement a broad, in-depth risk analysis. The likelihood of deliberate actions can be reduced by various types of security measures inside and around the building.

Study shows almost all construction failures in Sweden are attributed to gross errors in the building processes. Therefore, this category of events must always be placed in the list of the possible hazards that have to be managed. The likelihood of errors in the construction process is reduced by a better organization and effective quality control. According to the EKS 10 (2015), the design documentation has to be reviewed by an independent, external party. A comprehensive documentation of the design processes together with a qualified independent review significantly reduce the likelihood of errors in the building processes. An important part of the design documentation is reporting risk assessment with respect to accidental actions and progressive collapse.

Minimum structural integrity

In order to make sure that the structure possesses a certain minimum level of robustness, the structural system has to be designed such that the overall stability is ensured (Boverket, 2016). The minimum measure is to design key elements for a nominal load. A recommended load by Eurocode 1991-1-7 is a uniformly distributed load of 34 kN/m² for vertical elements. EKS10 (2015) recommends a load of 150 kN /m for beams and trusses. Besides, for the structural frames, e.g. for reinforced concrete and prefabricated concrete structural systems, the requirements on reinforcing connections in SS-EN 1992-1-1, 9:10 have to be fulfilled. For other types of building system, design should meet the corresponding requirements. EN 1992-1-1, 9:10 presents requirements in order to provide structural integrity. The following ties should be provided:

- peripheral ties
- internal ties
- horizontal column or wall ties.
- where required, vertical ties, particularly in panel buildings

5. Case Study- of Gekås P-Hus

This section attempts to design a building with respect to the structural robustness. The purpose of this study is to examine the proposed framework in the previous chapter for the analysis of structural robustness for an arbitrary structure. In the current study a simple qualitative risk analysis is applied for the building which is being studied in order to manage the risk of progressive collapse. However, there will be some buildings and structures such as offshore structures which demand advanced risk assessments.

5.1. System definition

The current case study is a 4-storey concrete framed parking garage planned for customers of Gekås Ullared superstore located in the city of Ullared in Sweden. As shown in Figure 5.1, the parking garage consists of two adjacent buildings. The parking is located near to the Ulla Smides road from one side and close to bäckvägen road from another side. The parking is mainly used by private cars, however, it is also used by loaders which transport shopping trolleys. Potentially it could be used by emergency vehicles. Truck traffic may occur, however, only trucks without trailers. The analysis has carried out based on the available documents of the building.

Double T precast concrete slabs are used for floors which are capable of withstanding high loads while having a long span. Precast concrete beams and columns are also used for the structural frame. The building will be structured with the span length of 17 m and the span distance of 7.2 m. Figure 5.2 shows beams and columns arrangement.

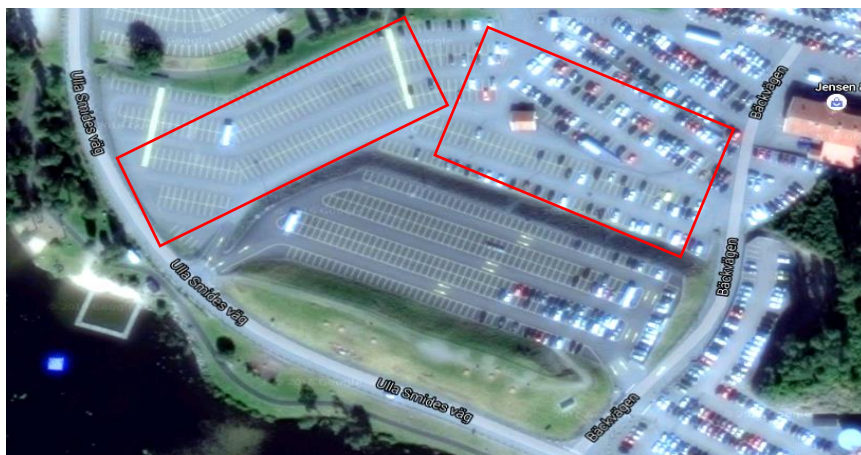


Figure 5.1. Site plan of the parking garage

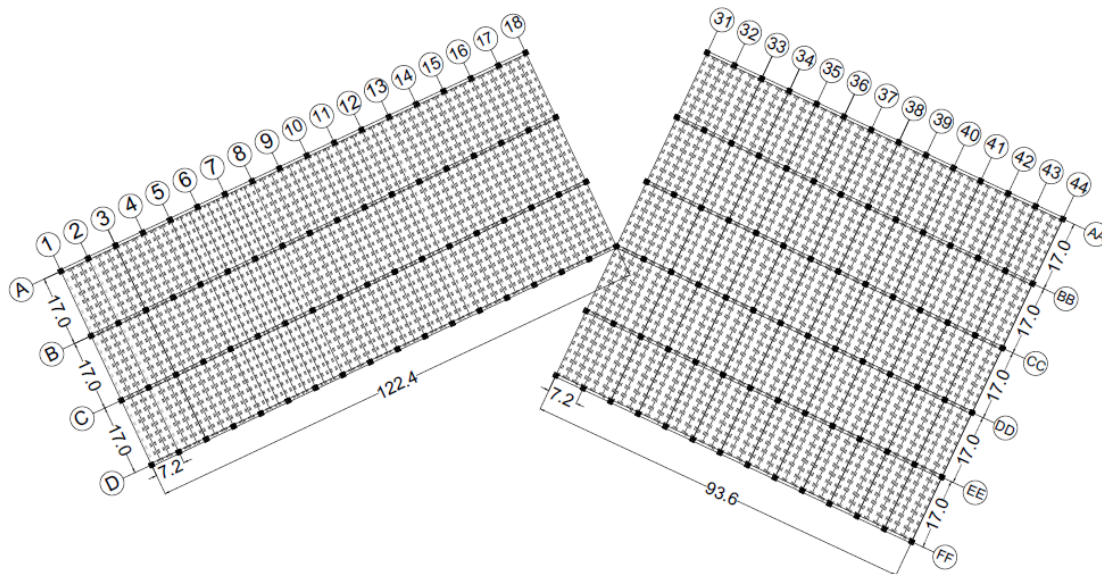


Figure 5.2. Beam and column arrangements

5.1.1. Selection of consequence class

The building is classified as consequences class 2b according to EN 1991-1-7, Table A.1. According to this classification, all parking garages having less than six stories are categorised in consequences class 2b. This classification, however, seems not reasonable because design of a six-storey parking garage against progressive collapse demands a different approach from a e.g. one-storey garage.

5.2. Hazard Identification

The starting point is to identify the hazards and threats to which the building might be subjected. This has been undertaken with help of the inventory of undesirable events in Table 4.1. This step is often considered as the most important step, simply because what has not been identified, will not be evaluated, and therefore cannot be mitigated. The hazards and threats are categorised as identifiable and unidentifiable events.

The review of the list of identified hazards has been carried out in a meeting in the presence of two structural experts. In some complex cases, structural engineer may involve other specialists such as architect, geotechnical engineer, blast engineer, client, etc.

It is assumed that the construction work is designed or will be designed to withstand normal loads, i.e. category 0 of table 4.1

5.2.1. Identifiable events

The analysis begins with evaluating the undesirable events in Table 4.1. The following initiating events have been identified:

- **Natural events:**

Extreme events such as hurricane, cyclone and tornado occur rarely in the region and the damages are mainly limited to the forests. Flooding are very unlikely to occur in the region of the building. The region has normal geotechnical conditions and events such as erosions, landslides, avalanche and eruption are not relevant in this area. Earthquake is not relevant for Sweden and can be neglected altogether. Consequently, the hazards from natural events with the potential of progressive collapse, is considered unlikely to occur.

- **Internal and external explosions**

The occurrence rates of internal explosions in buildings have been derived from an extensive survey performed in the UK (Moore, 1983). The values are 2×10^{-6} per year for dwellings and 6 to 14×10^{-6} for shops and industrial buildings. Present rates may be smaller due to improved safety measures. Although it seems unlikely that the parking garage is exposed to a substantial explosion as there is no gas installation in the building or in the vicinity, the following scenario seems possible:

Scenario 1. Explosive material inside vehicles

Certain explosives such as fireworks maybe carried by vehicles. The illegal carriage of explosives for illegal purposes is rare but possible. Therefore, there is the possibility of explosions in the garage although the consequences of such explosions with respect to progressive collapse is low.

The risk of explosion due to deliberate actions is evaluated later in the text titled as “Deliberate actions”.

Fire is an event that is considered relevant and has to be treated explicitly and comprehensively as a part of the standard design.

- **Accidental actions from traffic** (Helicopter/ airplane/ train /ship impact/ vehicles)

The nearest airport to the building is 68 km away. Besides, this type of hazard is mainly applicable for buildings with roofs designated as a landing pad for helicopters. Therefore, a helicopter/ airplane accident is not relevant in this case.

There is no rail traffic and ship traffic in the vicinity, therefore the risk from train and ship collision do not exist. Hence, the buildings do not need to be designed for this risk.

The risk of vehicle impacts is relevant and the following scenarios have been identified:

Scenario 2- Impact from road vehicles

Impact hazard seems likely in this case in which traffic collisions to one of the supports may cause disproportionate collapse. If a vehicle travelling along the roadway leaves the road at a critical place with sufficient speed, impact will occur to the structure. The hazard scenario is indicated in Figure 5.3. As apparent from Figure 5.1, the minimum distance, d , from the structure to the adjacent road is less than 10 meters which is less than the required safety distance (Table 5.1). Therefore, an explicit design with respect to the impact force is required. Table 5.2 presents equivalent static design values for impact by vehicles. Although equivalent static forces are commonly used in the design, this type of load is dynamic in nature. Impact analysis depends on the velocity and the mass of the impacting object, angle of impact, deformation behaviour and damping characteristics of both the impacting object and the structure.

d is the minimum distance from the construction to the center line of the nearest lane, measured perpendicular to the direction of traffic, see Figure 5.1.

d_b is the safety distance, can be determined according to Table 5.1.

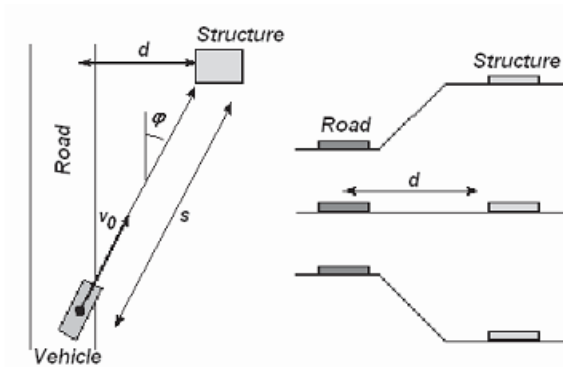


Figure 5.3. Definitions related to collisions with road vehicles

Table 5.1. Safety distances for different type of roads (CEN, 2006)

Type of road	Speed [km/h]	safety distance d_b^1 [m]
Motorway	90	20
Urban areas ²	50	10
Courtyards	15- 20	2
Parking garage	10	1
¹ d_b may be multiplied by 0.6 for the upward slope and 1.6 for the downward slope, see Figure 5-3.		
² Roads in areas with a maximum speed limit 50 km/h		

Table 5.2. Indicative equivalent static design forces due to vehicular impact on members supporting structures over or adjacent to roadways

Type of road	Indicative equivalent static design forces due to impact	
	Fd_x [kN]	Fd_y [kN]
Motorways and main roads	1000	500
Roads in urban areas	500	250
Country roads in rural area	750	375
Courtyards and parking garages with access to:		
-Cars	50	25
-Lorries	150	75

The critical structural components are the perimeter columns in the vicinity of the roads. The layout of critical columns is shown in Figure 5.4. Six different scenarios are suggested for the analysis based on which column is collided, A1, B1, C1, D1, AA44 and BB 44.

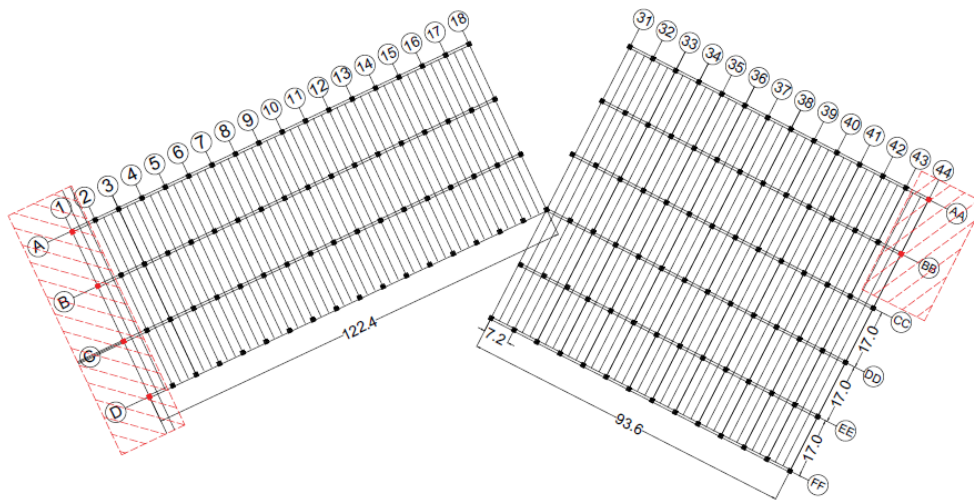


Figure 5.4. Critical columns

Scenario 3- Impact from loaders or trucks in the courtyard

The accidental actions caused by forklift trucks running in courtyard should also be taken into account. It is recommended in Eurocode 1991-1-7 that the design value of F is determined according to advanced impact design for soft impact.

Another undesirable scenario is colliding a vehicle running inside the parking garage to a column, but this is considered in the normal design.

5.2.2. Unidentifiable events

As it is obvious from the name, unidentifiable events are hard to identify and quantify. The current study aims to follow the proposed strategy 1 in order to control the risks of unidentifiable events, see the flowchart of Figure 4.2.

- **Deliberate actions (Terrorist attacks, etc.)**

There is not comprehensive statistics published about bomb incidents in Sweden. However, according to Siren's News Agency there have been recorded 1810 bombing events in Sweden between 2007 and 2012 (451 of events took place in Stockholm), of which 128 were bomb threats and 29 were bomb attacks [1]. It seems reasonable to exclude deliberate or malicious events from the scope of the risk assessment since the building does not have strategic role in the society. In general, the likelihood of terrorist attacks in building can be estimated based on the following characteristics (Vrouwenvelder and Leira, 2011):

1. The strategic role of the structure in society (energy supply, water supply, etc.)
2. The possibility of a large number of victims

3. The type of structure (monuments, embassies, governmental buildings, bridges, power stations, life lines).

Consequently, the risk of terrorist attack is considered unlikely to occur in the building.

- **Errors in the building process**

As highlighted earlier, error during building processes plays an important role in the construction failures in Sweden. In Sweden, only internal controls are required during the building process whereas an external control plays a major role in reducing errors. Different errors may be made during the building process:

Scenario 5- Gross errors in the building process

- design errors such as conceptual errors, misinterpretations of rules, calculating errors, software errors, drawing errors, etc.
- execution errors include misreading of specifications, bad workmanship, inferior materials, etc.
- other errors such as improper use, negligence in inspection, lack of maintenance and repair.

5.3. Risk evaluation

5.3.1. Probabilities

Estimating how likely certain events are, is often perceived as one of the most difficult tasks in a risk assessment. It is very difficult for these types of hazards and threats to determine how likely they are to occur while there is not much data about them. The likelihood scale is better to be adopted in accordance to life of the building. In this case, the likelihood can therefore only roughly be assessed according to the following scale:

- 1- Probable - corresponds to a prediction of one event in less than 50 years
- 2- Possible - corresponds to a prediction of one event in 50–100 years
- 3- Unlikely - corresponds to a prediction of one event in 100 years or more

5.3.2. Consequence

Consequences are generally expressed in terms of fatalities, economic loss or environmental damages. Obviously, consequences are not usually one-dimensional. In a qualitative assessment, experience, engineering judgement and approximate calculations can be used to estimate the consequences of hazards. As a simplification, the various consequences are divided into three categories:

1- Low: Failure of part of the structure. Substantial or partial collapse of structure unlikely. Small potential for injury and disruption to users.

2- High: Failure of part(s) of the structure with high potential for substantial or partial collapse and some potential for injury and disruption to users.

3- Severe: Sudden collapse of structure occurs with high potential for loss of life and injury.

5.3.3. Evaluate the risks

The likelihood and consequences of each scenario are assessed by reference to the scale in the previous sections. The risk from each scenario, therefore, is described qualitatively as a combination of likelihood and consequences.

Scenario 1. Explosive material inside vehicles

The likelihood of explosions due to the explosive material inside vehicles is judged as “possible”. Because enough ventilation is provided through windows in the parking garage, the generated pressure is greatly reduced. The consequences of such explosions are limited. Consequences are ascribed to “low” level.

Scenario 2- Impact from road vehicles

The likelihood of impact from road vehicles is judged as “probable”. The impacted column might be lost and may lead to partial collapse of the structure. Consequences are ascribed to “high” level.

Scenario 3- Impact from loaders or trucks in the courtyard

The likelihood of impact from loaders or trucks in the courtyard is judged as “possible”. The column will be damaged but will continue to carry self-weight. The consequence is ascribed to “low” level.

Scenario 4- Gross errors in the building process

The likelihood of errors in the building is judged as “probable”. However, the likelihood of errors sufficient to cause severe collapse is judged as “possible”. The consequence is ascribed to “severe” level. However, the total collapse of the building is unlikely, because in the pre-fabricated concrete systems, there are not such a continuity that lead to the total collapse.

5.4. Cause and consequence analysis

Identification of combinations or sequences of events leading to progressive collapse as well as influential factors is undertaken during cause and consequences analysis. In order to perform a cause and consequence analysis, an in-depth understanding of the system is required. For each initiating event, an analysis is carried out addressing the influential factors for each stage of scenario; initiation, damage and progression. This analysis provides a basis to assess the measures aiming at reducing the probability of an initiating event as well as assessing barriers in order to reduce the severity of the consequences. The results of analysis are described in the following tables.

Scenario 1

Stage of Scenario	Description	Influential factors
Initiation	Explosion due to explosive materials inside vehicles	- ignition sources - temperature
Damage	Failure of few structural elements	- congestion - confinement - protective systems - dynamic material behavior
Progression	Limited structural collapse	- level of redundancy of the structure - correlated component resistances

Scenario 2

Stage of Scenario	Description	Influential factors
Initiation	Impact from road vehicles	<ul style="list-style-type: none"> - velocity of vehicle - topographical properties of the terrain between road and structure - distance from roadside - the traffic intensity - poor visibility - unsafe coupling and uncoupling of trailers
Damage	A column loss	<ul style="list-style-type: none"> - ductility of the structure - dynamic material behavior
Progression	Local damage	<ul style="list-style-type: none"> - level of redundancy of the structure - correlated component resistances

Scenario 3

Stage of Scenario	Description	Influential factors
Initiation	Impact from loaders or trucks in the courtyard	<ul style="list-style-type: none"> - velocity of vehicle - the traffic intensity - poor visibility e.g. at blind corners - unsafe coupling and uncoupling of trailers - lack of suitable traffic safety features, e.g. direction, speed limit and priority signs
Damage	A column loss	<ul style="list-style-type: none"> - ductility of the structure - dynamic material behavior
Progression	Local damage	<ul style="list-style-type: none"> - level of redundancy of the structure - correlated component resistances

Scenario 4

Stage of Scenario	Description	Influential factors
Initiation	Gross errors in the building process	<ul style="list-style-type: none"> - competency of engineer - physical and mental conditions such as stress and time pressure - complexity of the task, completeness or contradiction of information - untried new technologies - communication and organization - poor quality control - lack of quality control procedure
Damage	Failure of few structural elements	<ul style="list-style-type: none"> - ductility of the structure - dynamic material behavior
Progression	Considerable structural collapse	<ul style="list-style-type: none"> - level of redundancy of the structure - correlated component resistances

5.5. Risk Reduction Measures

There are several strategies in order to reduce or eliminate the risks of hazards. These strategies depend on the stage of scenarios, initiation, damage and progression, see the following equation.

$$P(F) = P(F | D \cap E) \cdot P(D | E) \cdot P(E)$$

5-1

The following measures have been suggested for each scenario:

- **Scenario 1:**

1. Provide signs in the entrance and inside the parking and which warn carrying explosive materials.
2. Perform explosion simulations and design the structure to resist the explosion peak pressure.
3. Installation of emergency lighting on escape route

- **Scenario 2:**

1. Design the exposed structural elements to withstand the impact load, critical columns should be designed in a way to avoid brittle failure.

According to EN 1991-1-7. For impact from lorries the collision force F may be applied at any height between 0,5 m to 1,5 m above the level of the carriageway or higher where certain types of protective barriers are provided. The recommended application area is $a = 0,5$ m (height) by 1,50 m (width) or the member width, whichever is the smaller.

For impact from cars the collision force F may be applied at $h = 0,50$ m above the level of the carriageway. The recommended application area is $a = 0,25$ m (height) by 1,50 m (width) or the member width, whichever is the smaller.

2. Provide external barriers to prevent road vehicles from approaching.
3. Consider introducing a one-way traffic system to reduce the risk of collisions.

4. Check that suitable safety features are provided. Direction, speed limit and priority signs may be needed.
5. Determine whether physical speed restrictions such as speed bumps are necessary.
6. Compartmentalisation is relevant for long-span structures as the damage is limited to the adjacent spans. However, the structure is more vulnerable to the collapse during construction as it does not possess enough continuity.

- **Scenario 3**

1. Provide suitable fixed mirrors at blind corners.
2. Establish a traffic plan for the site
3. Ensure that trucks and pedestrians are segregated where possible
4. Check that suitable safety features are provided. Direction, speed limit and priority signs may be needed.

- **Scenario 4**

The measures presented for this scenario are considered as the most important measures because they have significant impact on reducing the risk of progressive collapse.

1. An external, independent check of the design process
2. Independent inspection during construction
3. Improve communication of information and results within the design team and supply chain,
4. Provide a risk assessment document
5. A peer review of the risk assessment
6. An updated external, independent check after designing the mitigation measures

5.5.1 Design suggestion/ consideration

At the earliest stages of design, there are higher opportunity to eliminate some hazards. Some hazards are eliminated or reduced through amendment in the design. The structural engineer must be aware that some measures that reduce the likelihood of a hazard, increase

the consequences at the same time, Therefore, it must be checked that any risk reduction measures, especially in the design of structure, do not increase the risks of other hazards.

There are some comments on how to improve the system by changing in the design

1. Large spacing between columns increases the extent of damage. In the current building the span length is 17 meter. If reducing the spans is not feasible, more attention should be given to design of columns.
2. Compartmentalization of the building is another suggestion. we sacrifice one part in order to save the rest of building in case of local damage.
3. Use cast in place concrete instead of precast concretes in order to gain higher level of ductility.
4. Risk assessment should be undertaken both at the conceptual design stage and updated when the design is finalised.

5.6. Risk presentation

For a qualitative assessment, a risk matrix is a convenient method of ranking the risks. However, for low probability-high consequences events, risk matrix may provide a poor representation. The risks arising from each scenario is plotted in the matrix, see Table 5.3.

The determination of the tolerable risks is not easy since the type of damage will differ according to each hazard. For more frequent accidental actions, no damage or minor damage is acceptable, while for very rare events such as terrorism greater extent of collapse may be deemed tolerable. For design against progressive collapse, area of collapse is usually used as a measure of consequences. In Eurocode, a collapse is judged proportionate if the area of collapse is less than 15 % of the floor, or 100 m², whichever is smaller, in each of two adjacent storeys.

It is assumed that the life time of the parking garage is 100 years. Utilizing likelihood as a frame of reference for tolerable risk, one might consider an event tolerable if it is predicted to have less than 1%¹ probability of occurring once during the lifetime of the building.

¹ Characteristic values in design codes for variable loads have an annual probability of being exceeded of 2%, equivalent to a return period of 50 years.

Table 5.3. Risk Matrix

Likelihood	3 – Probable (<50 years)		Scenario 2	
	2 – Possible (50-100 years)	Scenario 3 Scenario 1		Scenario 4
	1 – Unlikely(>100 years)			
		1 – Low	2 – High	3 – Severe
		Potential consequences		

5.7. Risk Treatment

The cost benefit analysis is usually used in order to choose between different mitigation measures. For the purpose of design against disproportionate collapse, a qualitative assessment based on engineering judgement is often sufficient. Since it is not straightforward to define a threshold in order to distinguish intolerable risks for structural robustness, the goal is to mitigate the risks as far as is reasonably practicable. During the expert meeting, the effect of the various alternative safety measures was assessed qualitatively. The following measures have been chosen to

Scenario 1: In order to manage the risk of explosion due to explosive materials inside vehicles, all proposed mitigation measures have been chosen to be implemented.

Scenario 2: In order to manage the risk of impact from road vehicles, mitigation measures number 2, 4 and 5 have been chosen to be implemented.

Scenario 3: In order to manage the risk of impact due to impact from loaders or trucks in the courtyard all proposed mitigation measures, have been chosen to be implemented.

Scenario 4: In order to manage the risk of impact due to gross errors in the building process, all proposed mitigation measures have been chosen to be implemented.

The effect of the modification through mitigation measures was assessed qualitatively, and the relevant likelihood and consequences were updated.

Table 5.4. Updated Risk Matrix

Likelihood	3 – Probable (<50 years)			
	2 – Possible (50-100 years)	<i>Scenario 3</i> <i>Scenario 1</i>		
	1 – Unlikely(>100 years)	<i>Scenario 2</i>	<i>Scenario 4</i>	
		1 – Low	2 – High	3 – Severe
		Potential consequences		

6. Conclusions and Discussion

A brief review of major progressive collapse events has been provided in the first chapter. After reviewing the definitions of robustness and progressive collapse, a general overview on the methodologies used for designing the structural robustness has been given. Eurocode presents prescriptive tie rules for structural robustness of medium risk buildings (consequence class 2a and 2b). The current tie force method is based on the minimum tensile force required for progressive collapse resistance. However, prescribing a force for a tie is misleading as it is deformation limits which are important in the case of local damage.

Tying is intended to absorb a substantial amount of local damage, however, it is not suitable in all cases. It is difficult to verify the ductility requirement in some systems such as precast concrete slabs, large-panel, bearing wall buildings, etc. The reliability of this overly simplified method is too uncertain and it cannot assure the redistribution of loads with confidence. Besides, it can sometimes be advantageous to separate the different parts of a building and therefore limit the extent of damage.

Several measures have been described in chapter 2 attempting to quantify robustness in order to define an acceptable level of robustness in the buildings. It seems reasonable to not achieve to a united measure of robustness, because there are masses of uncertainty regarding the events and consequences. Focusing only on those aspects which have enough information available to be quantified can lead to misleading results. Robustness, after all, focuses on those events that we have difficulty quantifying them in the first place. Consequently, the quantitative tie-force approach for robustness design is incompetent as robustness cannot be specified generally in a quantitative way and is very specific to the case being studied.

The dominating system used in Sweden for multistorey buildings includes precast concrete systems in which it is difficult to provide continuity and ductility. If a frame is cast in place, special attention to energy available in the system reinforcement at beam-column interface is needed. Realization of such behaviour for pre-cast structures is problematic. In some structures designed with tie-force method, that fail to redistribute the loads, which is very likely in precast concrete, continuity worsen the collapse of structure.

It seems not rational to follow a prescribed design procedure to ensure structural robustness of arbitrary buildings. Each building should therefore be investigated separately and specific design requirement for the robustness of the structure should be given.

A risk based approach aiming to overcome the mentioned problems has been examined for a real building in consequence class 2b. The main goal of the proposed approach is to identify, describe and communicate the main features of risks, vulnerabilities as well as mitigation measures with respect to disproportionate collapse and progressive collapse. This method requires a systematic identification of hazards and threats with respect to the building's location and characteristics. A four-storey parking garage has been analysed with respect to the list of hazards and threats given in chapter 4. The identified hazards and threats and associated scenarios have been reviewed by two structural experts. However, for more complex buildings, the process requires other technical competences in the required fields, such as geotechnical experts.

The scenarios have been evaluated qualitatively based on the estimated likelihood and consequence classes. Engineering judgement plays a major role in this risk assessment procedure due to high levels of uncertainty regarding likelihood and consequence of hazards. A quantified assessment may be required for certain hazards if further detail is required to assess the acceptability of the risk. However, a lack of accurate data on the likelihood of hazards may mean that a quantitative assessment is not always possible.

In order to find appropriate mitigation measures, cause and consequence analysis have been carried out. Referring to the equation 3-1, the probability of progressive collapse can be minimised in three ways, namely by: controlling events, controlling local damage and/or controlling global system behaviour. In the proposed approach, a great attention has been given to the cause analysis rather than consequence analysis. It describes a picture of the most important factors affecting initiation, damage and progression of each scenario. Consequence analysis, on the other hand, is accompanied by large uncertainties. The consequence analysis has been carried out roughly for the different stages of scenario.

Risk reduction measures have been proposed for each scenario, taking into account the influential factors. As described in chapter 4, in order to ensure a minimum structural integrity, requirements on reinforcing connections in SS-EN 1992-1-1, 9:10 have to be fulfilled.

The process ends with documenting the process of the systematic risk assessment. All sources of data, assumptions upon which the risk analysis is done in the assessment should be included in the report. The designer should ensure that information about mitigated risks and remained risk are communicated effectively. The report should include all hazards and their associated level of risk, explanations of why the risks are acceptable and which reduction measures have been necessary. Optional additional reduction measures may also be suggested to further reduce the risks.

To summarise, the feasibility of a risk-based approach for ordinary building has been examined for a real building. The analysis has shown that in the ordinary buildings, the Eurocode requirements for structural robustness could simply be replaced with mitigation measures and independent check of a third party. The analysis is relatively simple and basic specially for buildings where the risk of deliberate actions can be ignored. A more sophisticated analysis may be required for building in consequence class 3. As highlighted before, almost all construction failures in Sweden are attributed to gross errors in the building processes, therefore robustness is best controlled by quality control. Qualified independent review of both the design documentation and the execution process has to be implemented. However, quality control standards and prosedures may be needed in order to ensure the desired level of quality.

Engineering judgement plays a major role in the proposed approach, judgement about possible events, the consequences of these events, likelihoods and judgement about risk acceptability. According to this method, therefore, design for robustness cannot be transferred into precise and generic rules as desired by structural engineers and authorities. However, making judgements is an inevitable part of a good engineering practice. Consequently, it brings responsibility for the engineer carrying the design. One main obstacle to this approach would be resistance from engineers who tend to simply follow the rules as they do in the conventional design of buildings which is governed by code rules, while robustness cannot be treated by certain rules. It depends on specific properties of the building in a certain project.

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Appendix A

Table A. 1. Categorisation of consequences classes. The figures in the table refer to number of floors ^a

Type of building ^b	Consequence class			
	1	2A	2B	3
Houses ^c , offices, hotels		1-4	5-15	≥16
Single Family Home	1-4	5	≥6	
Retailing premises		1-3 and <1000 m ² /floor	4-15	≥16
schools		1	2-15	≥16
Hospital			1-3	≥4
Parking garages			1-6	≥6
Buildings that public access to		1-2 and <2000 m ² /floor	<5000 m ² per floor	>5000 m ² per floor
Stadia		< 2000 m ²	< 5000 m ²	>5000 spectators
industrial Buildings		1-3 and without high risk ^e		≥4 or with high risk ^e
Buildings that people rarely staying in	all ^d			
agricultural buildings	all			

a Refers to floors above the ground if basements are classified as Class 2 B.

b For buildings intended for more than one type of use the “consequences class” should be that relating to the most onerous type.

c Apartment buildings

d provided no part of the building is closer to another building, or area where people do go, than a distance of 1.5 times the building height.

e high risk related to the buildings containing dangerous goods or hazardous processes